chapter 4

Smart Silicon Sensors and the Real World

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Abstract

The silicon sensor field is now 30-40 years old and the commercial success of these sensors in the real world is not satisfactory. **In** this paper I present an analysis of the most important features of silicon sensors and claim that the main breakthrough will come as soon as low-cost smart sensor system with bus compatible output will reach the market.

Introduction

The silicon sensor field is 30-40 years old, though the term ‘silicon sensors’ was not used when the first devices were conceived. The first silicon sensors used silicon diodes for the detection of light, but soon Hall effect and piezoresistivity were also measured in silicon. The first silicon sensors were fabricated by means of the standard silicon planar technology, which was introduced around 1960 to make the first elementary integrated circuits. The silicon sensor field, as we define it today, really started around 1970 when Gieles [1] presented his miniature pressure sensor, Bergveld [2] his ISFET and Lundstrom [*3*] the hydrogen sensitive Pd-gate MOSFET.

In contrast to photodiodes and Hall plates, these devices required several non-standard processing steps. For instance, to shape silicon in the form of a beam or membrane, non-standard processes like bulk and surface micro machining were introduced.

Silicon sensors that, at present, are commercially available, are compiled in Table 1.Though this list might look impressive, in the real world only a few devices are sold with such large numbers that it can be called a commercial success. Therefore, industries and governments start to wonder if all the research and development money (a rough guess gives $ 10^{10} in the last 40 years) spent on silicon sensors has produced the expected financial return.

Research results on a multitude of silicon sensors have been presented in the international literature [4]. Many have very sophisticated and innovative features, but the commercial success is not very convincing.

It is now generally accepted that, in the years to come, only those sensors will be successful, which show distinct features that can not be obtained with existing non-silicon sensors. Silicon sensors should show a clear-cut “added value" in comparison to conventional sensors. In practical all cases it is also very important that the silicon
sensors can be manufactured at low cost,

Silicon sensors are promoted for several reasons. Silicon sensors are batch processed and therefore, promise to be inexpensive. A second reason *is* that thanks to the advanced planar technology and lithography silicon sensors can be made very small. A third reason is (hat silicon shows some interesting new effects which can be used to make novel sensors. However, the most important reason to use silicon for sensors is the possibility to integrate a sensor and its interface electronic circuitry on one and the same silicon chip leading to so-called "smart" sensors.

Table I Commercially available silicon sensors

Light sensors	photodiode, phototransistor, a'valanchephotodiode.Schottky photodiode, PIN photodiode, diodearray, CCD, infrared
Mechanical sensors	piezoresistive pressure sensor, capacitive pressure sensor, accelerometer, quadrant position sensor, position sensitive device (PSD)
Thermal sensor	sthermopile, spreading resistance sensor, PTAT temperature sensor
Magnetic sensors	Hall plate, magneto resistive field sensor
Chemical sensors	Sensor
ISFETs, hydrogen sensor	In the following sections cost and "added value" features like size, new effects and "smartness" will be critically assessed.

Low cost

Datch production of electronic circuits makes it possible to offer these components at very low cost. An often used characteristic value is the price of one mm1 processed, tested and encapsulated silicon. For a standard CMOS process this value is as low as

$ 0.25/mm2. When work on silicon sensors started, it was widely believed that this value would also apply to silicon sensors. In view of the fact that the price of conventional non-silicon sensors is between $ 100 and $1000, silicon, as a generic technology for sensors, looked very attractive indeed.However, when R & D on silicon sensors started some 20 years ago, it was not sufficiently realized that in order to achieve a low price with silicon devices, a very important condition has to be met, namely, a mass market must exist allowing batch fabrication.For most sensors in the real world, this is not the case. The measurement and control market, which, up to now, is the main customer for sensors, is dramatically fragmented. One author [5] even claims that about 50 000 different commercially available sensors exist for the measurement of about 100 physical parameters. In chemistry it is even worse. Here one needs specific (online) sensors that are sensitive to only one substance. In view of the huge amount of materials also a large number of specific sensors have to be developed. However, for most of these sensors the market volume will be rather small.

The production costs of an integrated circuit or sensor depends, as is shown in Fig.1, on the material costs,

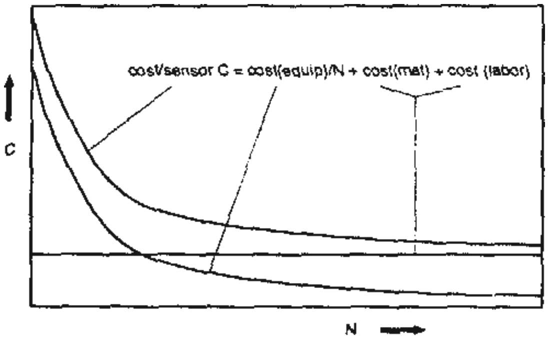

Fig. 1 Cost/sensor C as a function of the number *N* produced.

the labour costs and the equipment write-offs. In the semiconductor industry the production and labour costs per component are independent of the total number N of manufactured devices. In contrast, the write-off costs are inversely proportional to *N*. For products that can be made with very low equipment costs, the total cost per component is a constant. For such a component, the first produced component is as expensive as the last one. When labor costs are-relatively high compared to the material costs, a low and commercially attractive cost price can be achieved when production is moved to low-wage countries.

Unfortunately sensors do not belong to this category. Semiconductor manufacturing plants are extremely expensive. Nowadays, a modem 1C facility costs up to $ 109 and therefore, at small production numbers the equipment costs will dominate. Sensors made in small series will be (very) expensive and moving the manufacturing plant to a low-wage country will have little effect on this high cost price.

Since the equipment costs for non-silicon sensors are much lower than for silicon sensors, in small markets it will be very difficult to replace non-silicon sensors by silicon devices. Fortunately sensors are also needed for a number of mass-markets where the application of silicon sensors can be very lucrative. For example, the automotive and consumer markets require large quantities of sensors and only silicon sensors fulfill the high requirements with respect to functionality and cost. Silicon sensors like photodiodes, CCDs, Hall plates, pressure sensors, accelerometers, spreading resistance temperature sensors, nowadays, are sold in very large quantities-Infrared detectors for burglar alarms, flow sensors for vacuum cleaners and photo detectors for home illumination control will soon follow. In these markets labour-costs play an important role and moving production lo low-wage countries might be attractive. Size by virtue of the silicon planar technology, silicon sensors chips can be made very small containing fine structures down to OS micron. The small size and high accuracy have often a beneficial effect on the characteristics of the device such as frequency response and offset. The small size makes it also possible to position them there were conventional sensors cannot be placed because they are too large. In most applications this is not an important issue, as in most measurement and control equipment enough space is available for (non-silicon) sensors- In one application, however, size is certainly important, namely in the medical field. For instance in surgery it is a great advantage when the pressure in blood vessels can be continuously monitored during an operation. Also the possibility of brain pressure measurement might decide about life or death of a patient. For medical applications small sensor companies have developed miniature disposable pressure sensors at reasonable cost, which can be inserted by means of catheters.

Sensors for the measurement of temperature, blood flow and oxygen content might be possible products in the future. Also multifunctional human implants for gastro-enterology become feasible and might develop into a sizable market. The medical market certainly will further develop as the price per part can be somewhat higher than in the consumer markets. Moreover sensors that are used in the medical field can be used for only one patient. This is good for the sensor manufacturer, but not so good for the patient or the insurance company. The medical field seems best suited for medium sized sensor companies in as well high and low-wage countries. Cost, but even more creativity will decide about who is successful in this market.

New Functions

Silicon offers the potential of realizing new sensors by using physical effects that only occur in silicon or physical effects that are much larger in silicon than in other materials. For instance, silicon is an almost perfect mechanical material, showing no hysteresis. Silicon membranes and beams show nearly ideal behaviour until the breaking point. The absence of hysteresis makes it possible to make highly accurate mechanical sensors. Silicon also shows effects that are much larger (two orders of magnitude) than in other materials. Piezoresistivity and the Seebeck effect are good examples. The large piezoresistivity in silicon is used for the production of pressure sensors and accelerometers. Already in 1969 Gieles [1] showed that a pressure sensor can be built by micro machining a thin membrane of silicon and by diffusing a Whetstone bridge in the upper surface of this 'membrane. A pressure causes the membrane to bend and this will change the value of the resistors of the bridge. At present, practically all commercially available silicon pressure sensors depend on this mechanism. More recently also capacitive readout of the bending membrane is introduced.Also the accelerometers that are used for airbags today use the large piezoresistivity in silicon. The present accelerometers are based on the design as originally presented by Roylance and Angell [6] When the cantilever with seismic mass as shown in Fig. 2 is subjected to acceleration, it will bend.

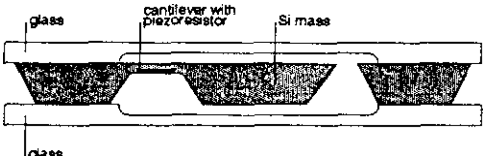

Fig. 2 Piezoresistive accelerometer.

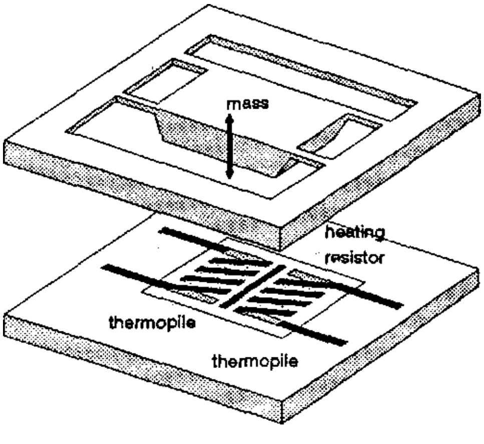

Fig. 3 Thermal accelerometer.

A piezoresistor in the thin part of ihe cantilever will detect the bending and the change of the resistance is then a measure for the acceleration. The pressure sensor and the accelerometer would be impossible, when the piezoresistivity in silicon would be as small as in the usual strain gauge materials. The large Seebeck effect in silicon can be used to make infrared sensors, micro calorimeters and even also accelerometers [7].

Figure 3 shows an accelerometer based on the Seebeck effect. The accelerometer consists of a seismic mass that is positioned above a Si3N4 membrane on which a resistance healer strip and two polycrystalline thermopiles are positioned. The thermopiles detect a temperature difference between the healer and the outside. When the seismic mass is subjected to acceleration and moves, the temperature pattern changes which can be detected by the thermopiles. The output signal is very large, because the Seebeck effect in silicon is much larger than that of other materials.

Smart silicon sensors present-day silicon and non-silicon sensors are often not suitable for application in modern data-acquisition systems. There are three reasons for this. First appropriate standards for the electrical output signals of sensors are tacking. Many output formats, like current, voltage, resistivity, capacity, frequency, phase or duly cycle, exist which makes replaceability a great problem. Secondly sensors, in general, show many deficiencies such as offset, drift and cross-sensitivity. To apply a sensor, system designers must be thoroughly familiar with its performance. Present-day system engineers seldom posses this knowledge. A third problem has to do with the ever-increasing digitization of data acquisition systems. In centrally organized measurement arid control systems, all sensors, controllers and actuators have to be connected by dedicated lines (based on the 4-20 mA standard). As the number of sensors in modern systems steadily increases, the total length of the connection lines becomes absurd. lo new cars, for example, 1 mile of connecting wires are required. Therefore, centrally organized systems will be gradually replaced by bus systems, where communication between the components will be in digital form, greatly reducing the length of connecting wires. These modern systems require a complete new generation of smart sensors or rather smart sensor systems- In the near future, a sensor system will consist of, in each case, the sensing element converting a non-electrical signal into an electrical signal. But it will also contain interface electronic circuitry for adapting output formats such that the sensor can be connected to a bus like the Field, Home or CAN bus [8]. The sensor will also contain circuits and other sensors and even actuators to abate offset, non-linearity, drift and cross-sensitivities. The sensor also needs address recognition circuits, as it must be possible for the controller to choose the sensor that has to respond.

In aircraft and large manufacturing plants bus systems already have been introduced on a great scale. Also a few automobiles are on the market where a bus system is used. However, it can be expected that sooner or later consumer products, like cameras, washers, vacuum cleaners and coffee machines will be introduced on the market, in which information transfer is solely based on communication along & bus and micro controllers.

Bus compatible sensor systems can be composed, in a hybrid fashion, from single components, already available on the market. For small series and try-outs this will be, for the time to come, certainly the most cost-effective approach. However, for consumer product such hybrid sensor systems will be far too expensive. In order to introduce bus systems on a great scale in consumer products the only practicable way to go is to integrate the sensor with all the needed electronic circuitry on one single chip. This will require very thorough knowledge of sensor physics, electronic circuits and bus systems. Smart sensor systems can only be mass-produced in standard 1C manufacturing plants. Then, materials and wages will play a dominating role. Therefore, smart sensor systems offer great opportunities for low-wage countries. Also the hybrid versions based on existing components and suitable for small markets can offer great challenges to the same countries.

Conclusions

In spite of the large amount of research money spent on silicon sensors and the large number of scientists working in the Held, the commercial success of silicon sensors has been rather modest until now. Evidently to be successful in the real world there must be a powerful incentive to use silicon sensors. Fortunately, for many application areas, these incentives exist. To begin with, silicon sensors can be mass-produced at very low cost and consequently can be introduced in automobiles and consumer products for which mass markets exist. Secondly silicon sensors can be made very small. This makes them ideal for medical applications. Silicon sensors might even turn out to be the only solution for the invasive measurement of pressure, motion, acceleration, blood flow, blood oxygen content and pH. However, the most attractive application area for silicon sensors will undoubtedly be the smart-sensor system field. Smart sensors will be a must in smart buildings and homes, smart traffic-control systems, smart cars, smart copiers and a large group of smart consumer products. Hybrid smart sensor systems will, in almost all cases, not be cost-effective. Therefore, completely integrated versions have to be developed. These sensor systems should be easily replaceable and should show features like auto calibration and self-test. It is very improbable that small manufacturing plants can offer the combination of high quality and low price required for these applications. For low-wage countries integrated smart sensors seems a very challenging field of endeavour.

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